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ORIGINAL PAPER

Daily precipitation intensity projected for the 21st century: seasonal changes over the Pyrenees

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Abstract A set of climate parameters (mean precipitation, number of wet days, daily intensity, and number of days with more than 50 mm rainfall) and a quantile-based approach are used to assess the expected changes in daily precipitation characteristics over the Pyrenees predicted for the 21st century using a set of regional climate models (RCMs). The features of the geographic location and topography of the Pyrenees imply that the climate of the region is highly complex. The results point toward an intensification of extremes, with a generalized tendency toward increasing drought periods, an increasing trend in daily intensity, and an increasing contribution of intense events to total precipitation; however, the results are subject to substantial spatial and seasonal variability, mainly related to the Atlantic-Mediterranean gradient and the longitudinal disposition of the main axis of the range.

1 Introduction

In light of recent climate trends and current predictions for the 21st century, climatic change is becoming a major concern for scientists, politicians, and society in general. Despite the uncertainty inherent in predicting and understanding precipitation in a greenhouse climate (Giorgi 2005; Räisänen 2006), this remains a key task because precipitation is important in terms of water supply, economic activities, ecosystems, and the assessment of natural hazards. The improved resolution of climate models has led to advances in this field, and such models are now able to provide reliable estimates of the spatial distribution and magnitude of precipitation, even for episodes of heavy rainfall (Fowler et al. 2005; Beniston 2006; Beniston et al. 2007; Boroneant et al. 2006; Frei et al. 2006).

A large number of studies have sought to estimate changes in precipitation and thereby assess the future availability of water resources. In contrast, few studies focus on potential shifts in the statistical distribution of daily precipitation series (e.g., Durman et al. 2001; Christensen and Christensen 2003, 2004; Frei et al. 2003, 2006; Ekström et al. 2005; Boroneant et al. 2006; Beniston 2006; Beniston et al. 2007). Daily precipitation is closely related to the frequency, magnitude, and duration of droughts and the occurrence of floods and associated geomorphic processes such as erosion and the initiation of landslides (Easterling et al. 2000; Nadal-Romero et al. 2007). Moreover, changes in the probability distribution of daily rainfall have an effect on runoff generation (Martin-Vide 2004), potentially either reinforcing or counteracting the impact of climate change on the availability of water resources. Existing studies in this regard (i.e., Karl et al. 1995) report a global tendency during the 20th century toward an increase of the frequency of extreme drought and flood events as a consequence of the concentration of precipitation within a smaller number of rainfall events; however, these generalized results hide a large degree of spatial and seasonal variability (e.g., Groissman et al. 1999; Brunneti et al. 2001; González-Hidalgo et al. 2003). The above observations demonstrate the necessity of additional research at varied geographical sites to fully understand

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spatial variability in the impacts of climate change, for which there remain numerous gaps in our knowledge.

The purpose of this paper is to analyze the expected changes in the distribution of daily precipitation in the Pyrenean Mountains and surrounding areas for the end of the 21st century, as determined from modeled precipitation derived from an ensemble of six different regional climate models (RCMs). Analyses are performed in terms of changes in the frequency of dry and wet days, intensity of precipitation (PI), and extreme precipitation events (precipitation >50 mm/day). A quantile-based method was applied to detect changes in the influence of events from different parts of the frequency distribution on total precipitation.

The proposed study area (Fig. 1) was selected on the basis of a number of advantageous features. First, the region is subject to frequent extreme climatic events related to periods of water scarcity and severe floods events. In recent decades, such events have caused major economic losses and fatalities (White et al. 1997; López-Moreno et al. 2006). Second, the Pyrenees play a key role in water management of the surrounding areas, especially within the semi-arid lowlands of the Ebro Basin. Finally, a short distance (approximately 400 km) across the Pyrenees gives rise to marked climatic diversity from Atlantic (west) to Mediterranean (east) climates. In addition, the Pyrenees are an important mountain system, with many peaks exceeding 3,000 m a.s.l., and macrorelief is able to modulate largely the process of climate change. Extreme precipitation events in the Pyrenees can occur at any time throughout the year, but they tend to occur most frequently during winter and autumn in Atlantic areas and periodically during autumn in Mediterranean areas (García-Ruiz et al. 2001). These factors make the Pyrenees an interesting region in which to analyze spatial and seasonal variations in terms of climate change effects.

2 Data and methods

This study makes use of daily precipitation data modeled by a set of six different RCMs: HIRHAM: Danish Meteorological Institute (DMI); HIRHAM: Norwegian Meteorological Institute (METNO); HADCM3: Hadley Centre (HC); RCAO: Swedish Meteorological and Hydrological Institute (SMHI); REGCM: International Center for Theoretical Physics (ICTP); and PROMES: University Complutense of Madrid (UCM), all of which were driven by the GCM HadAM3H (related information and basic references of the used RCMs can be consulted in http://prudence.dmi.dk). Changes in precipitation under a greenhouse climate were assessed by comparing the modeled precipitation for current conditions (1960–1990) with those predicted for the future (2070–2100) under the A2 emission scenario. The A2 scenario assumes strong increases of atmospheric greenhouse gases in upcoming decades (Nakicenovic et al. 1998) and is the most used by the scientific community to assess the impacts of climate change at the end of the 21st century (Christensen and Christensen 2003, 2004; Frei 2006; Beniston 2006; Beniston et al. 2007; Blenkinsop and Fowler 2007; Mellander et al. 2007).. The resolution of the RCMs was close to 50 km (grid spacings of 0.44–0.50°). Observed data collected at four locations (see Fig. 1) were used to assess the skill of the RCMs in reproducing various characteristics of the daily precipitation series.

Changes in accumulated precipitation and number of wet (>1 mm) and dry (≤1 mm) days were accounted at seasonal basis; all changes are reported in percentage terms. Switches on extreme precipitation events are considered in terms of the difference in the occurrence of events greater than 50 mm day^{-1} between future and current conditions. This threshold (50 mm day^{-1}) has been used in previous studies (e.g., Karl and Knight 1998) and it is appropriate to be used for the Pyrenees, because it identifies intense events that have the capacity to trigger floods and geomorphic processes (García-Ruiz et al. 2003). The present-day expected recurrence interval of events with this intensity ranges in the region from 5 to 45 years (Beguería and Vicente-Serrano 2006).

In applying the quantile-based method, ten classes were defined from quantile thresholds estimated for the control period (1960–1990). The series of wet days, sorted in ascending order of amounts, are divided into groups that

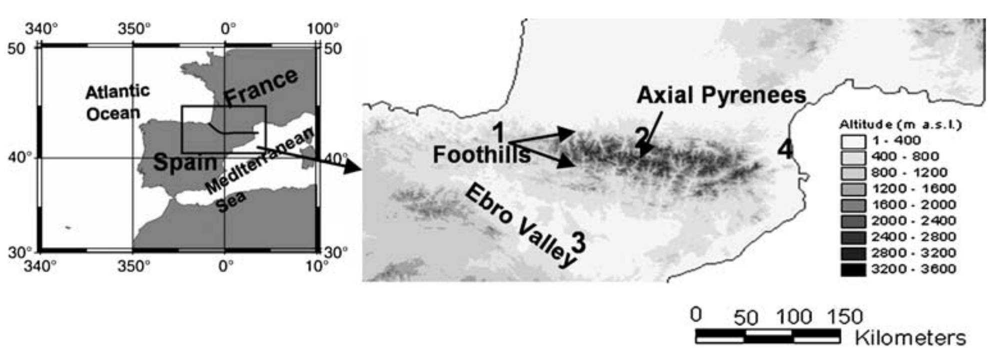

Fig. 1 Study area and location of the sites used for validation. *1* San Sebastian (S.Seb); *2* Tarbes (Tarb); *3* Zaragoza (Zgza); *4* Perpignan (Perpig)

each contributes 10% of the total precipitation (for details of this method, see Osborn et al. (2000). The upper limit of each class constitutes a threshold that was used to account for the contribution of each class during the A2 runs (2070–2100) compared to the control period. This approach enables quantification of the changing influence on total precipitation of events belonging to different parts of the frequency distribution. Figure 2 shows an example of the estimation of changing values for a particular grid -cell.

As the different RCMs use different coordinate systems, the outputs of the different models cannot be directly compared. To overcome this problem, we interpolated the seasonal and annual climatic variables (the change in total precipitation, number of wet days, days above 50 mm, and changes of the contribution of the ten defined classes) using a local robust method of splines. Climatic layers were interpolated within a common Lambert projection with a cell size of 20 km. Once all of information was matched in a common reference system and we had confirmed a significant correlation between the grids provided by the different RCMs, we averaged the obtained results to capture the mean signal of change predicted by the six models (largely following the procedure described by Holt and Palutikof (2004).

In applying the quantile-based method, we obtained ten results for each pixel within the study area and for each season. Each result consisted of the difference between the percentages of the precipitation amount accumulated within each of the ten classes defined by the thresholds obtained in the control period relative to the predictions of the A2 scenario. We performed a rotated principal component analysis (PCA) (Richman 1986) to synthesize the results and thereby identify areas for which similar patterns of change are predicted. The PCA reduces a large number of interrelated variables to a few independent principal components (PC) that capture much of the variance of the original data set (Hair et al. 1998). The rotation procedure allows a clearer separation of components that maintain their orthogonality and concentrates the loading for each PC onto the most influential variables (Hair et al. 1998). For PCA, the variables to be summarized were the average change observed in each of the ten classes and for each grid cell. A spatial classification of the target region according to similar patterns of change throughout the ten classes was carried out using the factorial loadings for each component, grouping the cells according to the maximum loading rule (Vicente-Serrano 2006).

3 Results

Figure 3 compares different precipitation parameters obtained from the six RCM simulations of seasonal precipitation for the control period (1960–1990) and for those grid points closest to the four locations with observation data for the same time slice. Despite some discrepancies between the predicted and observed data, the RCMs show a degree of skill in simulating the magnitude and seasonal patterns of average precipitation amount, average number of wet days, and number of rainy days above 50 mm. The figure also shows that predictions vary from one model to another which means a certain degree of uncertainty to be considered for an adequate interpretation of the results (Räisänen 2006). A previous study also detected differences in the projected mean temperature and total precipitation by the end of the 21st century in the Pyrenees. Such differences mainly affected to the magnitude of the expected change; but the sign, the seasonal

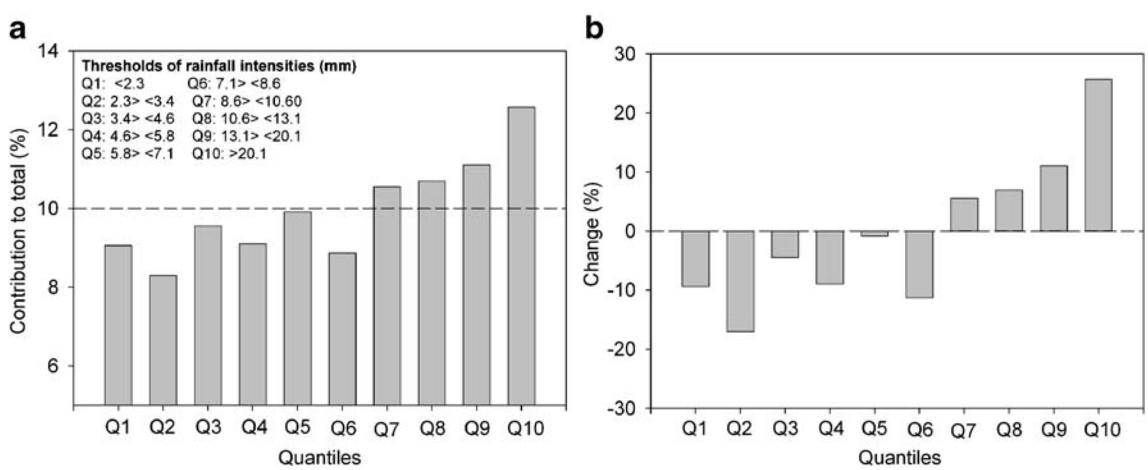

Fig. 2 Procedure followed for estimating quantile changes for a particular grid cell (where Perpignan is located). **a** Contribution to total precipitation in the future (A2) of events belonging to each of the ten classes defined by the thresholds obtained in the control period. **b** Changes between the percentages of the precipitation amount accumulated within each of the ten classes according to predictions of the A2 scenario with regard the 10% of contribution during the control period

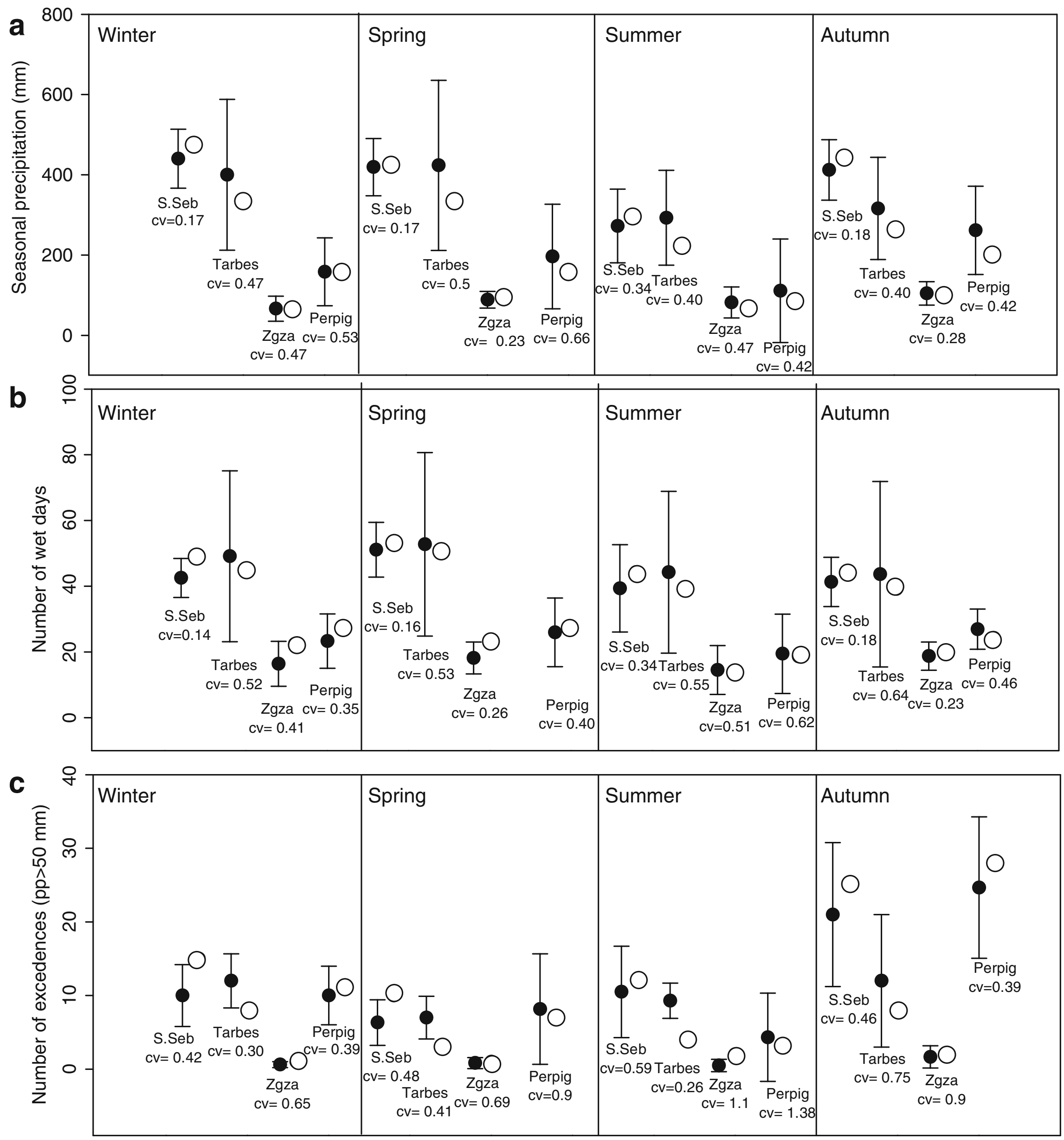

Fig. 3 Validation of average precipitation amount, average number of wet days per season, and total number of rainy days above 50 mm in the period 1960–1990 for RCM outputs (average of six RCMs (*black dots*) and ±1 std. deviation;) against observations taken at four observatories (*white dots*). *1* San Sebastian (S.Seb); *2* Tarbes (Tarb); *3* Zaragoza (Zgza); *4* Perpignan (Perpig). CV informs of the coefficient of variation (standard deviation divided by the average) of the six model projections

pattern and the spatial distribution of the changes remained rather similar amongst the different RCMs (López-Moreno et al. 2006). Inter-model variability, expressed by the standard deviation and the coefficients of variation, changes noticeably amongst locations, parameter considered (total precipitation, number of wet days and days above 50 mm) and season. In all cases, the inter-model averages provide an adequate approximation of the observed values.

Figure 4 shows seasonal changes in the average number of wet days (color scale) and average precipitation amount (isolines). The relationship between changes in the average precipitation amount and number of rainy days enables us to detect potential shifts in the degree of daily intensity (precipitation per wet day). The results show a general decreasing trend in the average number of wet days and the average precipitation amount; however, the magnitude and even the sign of the changes vary markedly in space and for different seasons. In winter, changes in average precipitation amount define a northwest–southeast gradient, with an increase of up to 10–15% in the northwest and a decrease of up to 20% in the southeast. Changes in the average number of wet days show a similar pattern for the totals in both spatial distribution and magnitude; however, in the Mediterranean sectors, the decrease in average precipitation

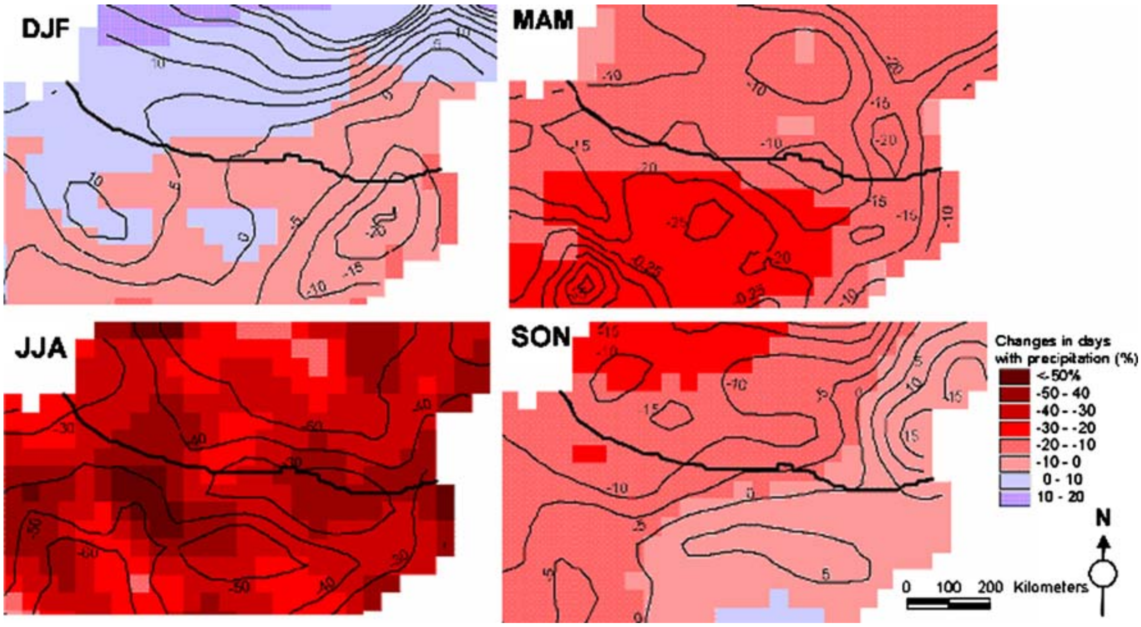

Fig. 4 Predicted seasonal changes in the average number of wet days (*color scale*) and average precipitation amount (*isolines*)

amount exceeds that expected for wet days, indicating a downward trend in precipitation intensity. In spring, a decrease in average precipitation amount (generally exceeding 10%) is observed across the whole region, being most intense upon the southern slopes of the Pyrenees where the average precipitation amount is predicted to decline by up to 35%. In the Atlantic sectors, as well as for the northern slopes of the Pyrenees (French side) and the Mediterranean coast, precipitation amount falls by 10–20%, yet wet days decrease by up to 10%, indicating an increase in daily intensity. Intensity remains approximately stable in the Spanish interior.

Summer records the highest precipitation, exceeding 30% in all areas and up to 60% in parts of Spain. Variation in daily intensity is less pronounced, with slight increases around the Spanish-French border and in some Mediterranean sectors and decreases in the northernmost and southernmost sectors of the region. The obtained trends for autumn are almost opposite those for winter, with a slight increase in precipitation amount (up to 15%) in the Mediterranean sectors and a progressive westward fall of up to 15% along the Atlantic coast. There is a general trend toward an increasing concentration of daily precipitation, especially along the Mediterranean coast where the precipitation amount is projected to increase but the number of wet days is projected to fall.

Figure 5 shows the spatial distribution of areas with similar patterns of change in terms of the contribution of the ten classes. PCA reveals the general patterns of predicted change between the control period and the A2 scenario. Table 1 lists the mean change in the contribution of each class for those areas that share a maximum correlation with one of the mapped components.

In winter, the two main components (77% of accumulated variance) indicate marked increases in the contribution of the highest classes (C1: 21%; C2: 36%), but the behavior of the remaining classes does not follow this pattern. Thus C1, which dominates the southwestern part of the region, is characterized by an increase in the lowest classes and a decrease in the highest ones. A near opposite pattern is observed for C2, which represents the Mediterranean sectors. In spring, two components explain 74% of cumulated variance. C1(northern and northeastern areas) is characterized by a clear increase in the contribution of the highest class (47%). Component 2, which represents large areas of the south and west, shows the increasing contribution of the two lowest classes, with the remaining classes showing no change or slight decreases. In summer, 72% of the variance is explained by the first three components. Only C1 shows a clear spatial pattern, with an increase in the contribution of the most intense events in the central part of the study area. In autumn, the first two components explain 86% of the variance. C1 is represented across almost the entire region, indicating unchanging behavior in the contribution of all classes except those events above quantile 10, which show a marked increase in their contribution to total precipitation. Areas along the French Mediterranean coast and within the Spanish interior (C2) record a decrease in the contribution of the lowest classes and an increase in that of the highest ones, especially the ninth and tenth classes.

The increase in the upper classes for most regions and seasons deducted by the quantile-based method does not lead always to an increase in the frequency of the most extreme precipitation events. Figure 6 shows the spatial

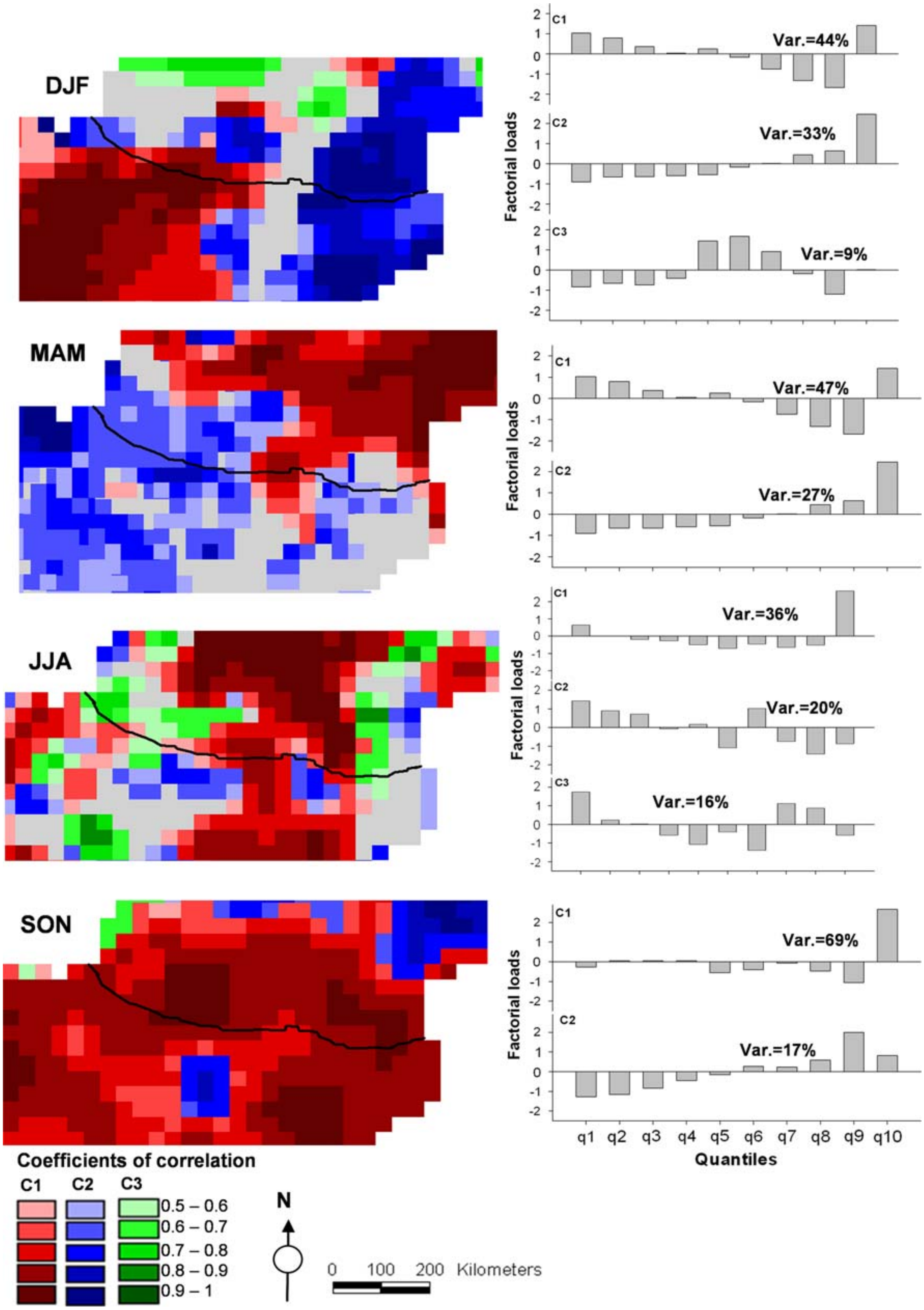

Fig. 5 Areas with similar patterns of seasonal change in the contribution of the ten defined classes. *Colors* indicate areas represented by each principal component according to the maximum loading rule. The color scale represents the correlation coefficient of the observed pattern for each cell with the pattern defined for each of the principal components. Bar graphs represent the loading factors of each component

Table 1 Mean changes (%) in the contribution of each class within the representative sectors of the identified principal components

		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
DJF	C1	−11.4	−8.6	−8.8	−7.2	−5.1	−1.8	−0.4	1.5	5.2	36.5
	C2	12.0	9.1	3.5	0.2	−0.4	−5.8	−9.4	−14.4	−16.5	21.7
	C3	−7.6	−5.4	−4.8	−3.3	6.1	10.5	7.5	5.1	−7.0	−1.1
MAM	C1	−1.1	−7.0	−8.9	−9.1	−5.1	−4.2	−3.4	−3.6	1.2	41.6
	C2	15.1	6.5	1.5	−0.7	−2.2	−4.8	−8.0	−4.8	−4.0	1.9
JJA	C1	19.5	4.1	−1.9	−4.8	−9.1	−11.4	−12.0	−12.6	−7.9	36.2
	C2	28.0	16.8	8.7	1.6	−1.0	−9.8	2.6	−11.3	−25.2	−10.4
	C3	26.8	7.3	1.6	−5.2	−11.1	−7.6	−15.6	2.4	1.1	0.2
SON	C1	−9.8	−12.7	−13.4	−14.5	−13.4	−10.3	−7.7	−3.3	4.6	77.6
	C2	−15.6	−17.1	−15.7	−12.7	−6.8	−3.6	−4.4	3.1	26.2	44.2

distribution of the expected percentage change in the frequency of events greater than 50 mm day^{-1} between the control period and the A2 scenario. The predictions reveal a greater frequency of extreme rainfall events in autumn, with increases ranging from 15% to more than 35% across the majority of the studied area. In addition, extreme events are expected to increase in frequency during winter in the western part of the Spanish territory and contiguous French side, but predicted to decrease in frequency in the Mediterranean areas and across wide areas of French territory. A generalized decrease in the frequency of extreme events is predicted for spring, especially on the Spanish side of the Pyrenees. During summer, the A2 scenario predicts a dramatic reduction in the frequency of extreme precipitation events across the entire region.

4 Discussion and conclusions

This work analyzed the expected changes between the present and the end of the 21st century, in different parameters that characterize the daily precipitation structure, with an emphasis on those parameters related to extreme events. Conclusions on the future behavior of daily precipitation parameters based on RCMs are subjected to a large number of uncertainties (Frei et al. 2003; Giorgi 2005) and results must be interpreted with caution. However, RCMs can be considered currently as the best available information regarding climate projections, and the comparison of estimated parameters from control runs with observations in the study area shows a rather good capability to represent the spatial variability of magnitude

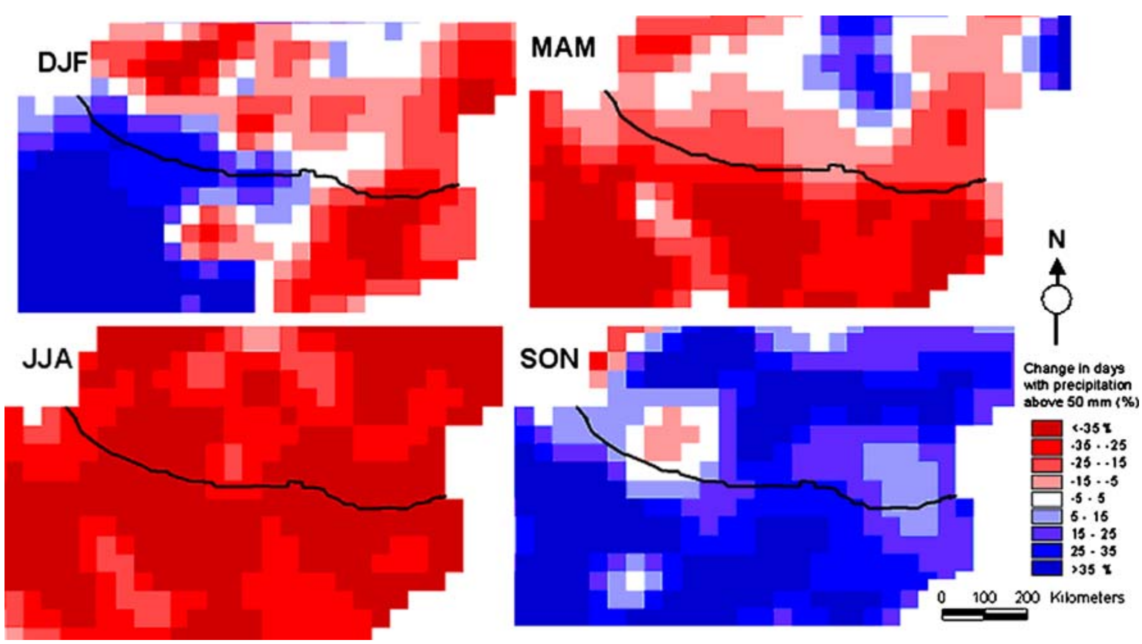

Fig. 6 Spatial distribution of predicted changes in the frequency of events above 50 mm day^{-1}

and seasonal distribution of the daily precipitation characteristics. The main findings of this study are as follows:

- A general decrease in precipitation is expected for the region, particularly marked in spring and summer.
- Daily precipitation intensity will tend to increase in the region, mainly in Mediterranean areas.
- In a future climate, the RCMs used in this study project a significant increase in the influence on total precipitation of those events with an intensity that currently contributes to the upper 10% of total precipitation. Changes for the rest of the frequency distribution are subject to large spatial and seasonal variability.
- The marked increase in the contribution of events belonging to the upper class cannot be directly related to an increasing frequency of extreme events (pp > 50 mm) because changes in both parameters show often contrasting spatial and seasonal patterns. Extreme events are predicted to increase in Atlantic areas during winter and across the entire region during autumn. A lower frequency of extremes events is predicted for spring and summer.

The use of a quantile-based method (Osborn et al. 2000), employed previously only to analyze historical records (Brunetti et al. 2001; López-Moreno et al. 2006), reveals the potential of this approach in detecting changes throughout the frequency distribution of daily precipitation records via the outputs of climate models for the end of the 21st century.

In line with previous observations of climate (Brunetti et al. 2001) and predictions for the entire Mediterranean basin (Gao et al. 2006) and southern Europe (Blenkinsop and Fowler 2007), the obtained results reveal a generalized intensification of extremes in the target region. The model scenarios predict that precipitation will decrease markedly in the region, especially in spring and summer. This reduction is related to a marked decrease in the frequency of wet days. This observation points toward an increase in the frequency and duration of the long dry spells that already affect the region (Martin-Vide 1999; Lana et al. 2007), leading to an intensification of the drought conditions that periodically strike the region and cause important economical losses in agriculture and result in widespread water restrictions (Vicente-Serrano 2006).

The model predictions suggest that future precipitation will tend to occur during fewer events, implying an increase in daily intensity. Our analysis using the quantile-based method reveals that most of the region will see an increase in the proportion of total precipitation provided by the most intense events.

A higher frequency of extreme precipitation events is also predicted for Atlantic areas during winter and for the entire region during autumn, even in sectors for which a pronounced drying is predicted. An increase in the frequency of intense precipitation events has been observed at many different sites during the 20th century (Brunetti et al. 2001 and references therein), and this is also predicted for most of the European region as a consequence of moistening of the atmosphere under warmer conditions (Katz and Acero 1994; Frei et al. 2006; Beniston et al. 2007); however, the predictions also show a general decrease in the frequency of these events during summer, as predicted previously by Frei et al. (2006) for southern Europe. An increase of both precipitation intensity and number of dry days has been also detected for the southwestern Mediterranean basin according to the mean projection of a set of different GCMs and under different emission scenarios (Tebaldi et al. 2006).

Even taking into account the relatively small size of the present study region, our results demonstrate marked spatial and seasonal variability in the impacts of climate change on precipitation, mainly in complex climatic areas. Thus, the obtained predictions for upcoming decades in this region are similar to those of previous studies that considered wider geographical areas, in particular the southwest Europe and/or the western Mediterranean basin (Frei et al. 2006, Gao et al. 2006). However, the scale employed in the present study enables a detailed description of the spatial and seasonal distribution of the predicted impacts, which may be subject to important changes in very short distances.

The Atlantic-Mediterranean gradient is prominent in the spatial distribution of predicted changes in all of the indicators considered. The severity of the gradient mainly reflects the short distance between two water bodies with marked differences in temperature and dynamics, as well as the fact that the relief of the Pyrenees acts to modify the impact of different atmospheric patterns across very short distances (Vicente-Serrano and López-Moreno 2006). In addition, the dominance of a longitudinal development of the main axis of the Pyrenees leads to clear differences between the northern and southern slopes of the range. These observations reveal the complexity of mountainous areas in assessing spatial variability in the impact of climate change on precipitation patterns, as documented previously in other mountainous areas such as the Alps (Frei et al. 2006).

The variable spatial and seasonal distributions of the projected changes throughout the study region have profound implications for the nature and magnitude of associated hazards. Thus, a major drying of the region is projected for the southern slopes of the Pyrenees during summer, coinciding with the sector and the season that are currently most strongly affected by drought conditions. In the same way, an increase in extreme precipitation is predicted for wintertime in Atlantic areas, where such events are already particularly frequent and intense. The generalized enhancement of events greater than 50 mm during autumn is especially preoccupying for those Mediterranean areas that currently endure damaging and sometimes fatal autumn floods. Thus, the projections obtained for daily rainfall parameters appear to indicate increased risks for the most vulnerable areas during the seasons with greatest risk of extreme hazards. These results highlight the necessity of further analyses at detailed spatial scales, especially for areas that are climatologically complex and highly vulnerable in terms of water resources management and exposure to natural hazards.

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